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A low-cost built-in self-test method for resistive MEMS sensors

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Abstract

This paper illustrates the experimental application of the LIMBO method, an identification method based on binary observations dedicated to the (self-) test of integrated electronic and electromechanical systems, such as MEMS. The tested MEMS device is a micro-wire used as a heating resistor, inserted in a Wheatstone bridge. We show how the impulse response and the offset of the micro device are estimated only using binary inputs and outputs and straightforward calculations, which can easily be implemented on an FPGA. This approach only requires a 1-bit ADC and a 1-bit DAC, which makes it very amenable to integration and highlights its suitability for the test of systems based on resistive sensor and/or actuator.

Keywords: parameter estimation; built-in self-test; MEMS; resistive sensors.

1. Introduction

The scaling-down of the characteristic dimensions of electronic devices and systems leads unvaryingly to a greater dispersion of their performances. Variations in the micro-fabrication process or changes in the operating conditions, such as temperature or ageing, are typical sources of dispersion. As a consequence, self-testing or self-adjustment are very desirable features for micro-fabricated devices. Most existing system identification methods [1-2] rely on the implementation of a high-resolution digital measurement of the system's output using an N-bit Analog-to-Digital Converter (ADC) where $N \gg 1$, which requires a long design times as well as a large silicon area. The Basic Identification Method using Binary Observations (BIMBO) and its online equivalent LIMBO have been presented in [3-4] as alternative self-test identification methods, requiring only a 1-bit ADC (with small silicon area and minimal energy consumption) and, for the online method, low memory storage requirements.

The present paper shows for the first time the experimental implementation of LIMBO (LMS-based Identification Method using Binary Observations). This work being focused on the evaluation of the performances of the LIMBO method, the start candidate is here a MEMS micro-wire used as a heating resistor, chosen with regards to its great ease of use. The trial device is a 1.5kΩ, 5µm × 20µm × 1500µm Silicon-On-Insulator (SOI) processed micro-wire, deeply under-etched (Fig 1). Under-etching enables the micro-wire to be set over a 300 μm thick gas layer. When heated by a current $i(t)$, where t denotes time, the temperature of the wire increases. The transient excess temperature of the wire, $\Theta(t)$ can be expressed by $\Theta(t) \propto h(t) * i^2(t)$ where $*$ denotes the convolution operator and where $h(t)$ is the unity

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Fig. 1. photograph of the SOI processed MEMS micro-wire used for the evaluation of LIMBO. On top side, the micro wire in contact with the silicon bulk (R_{W_0}), on bottom side the same micro-wire with deep under-etching ($R_{W_0} + \delta R_W(t)$). Color stands for Silicon (dark), gold contact (yellow), thin film insulator/SiO_2 (purple), silicon bulk (gray).

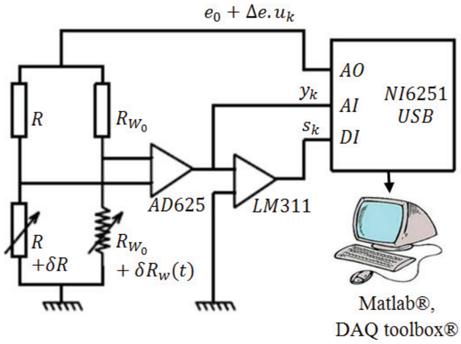

Fig. 2 Experimental setup. The micro-wire is placed on the bottom-right side in the Wheatstone bridge. The bottom-left side variable resistor is used to control the offset of the bridge.

gain impulse response of the wire, expressed in the time domain. Following [5-6], we have:

$$h(t) = \sum_{n=0}^{\infty} g_n.exp\left(-\frac{t}{t_n}\right) \cong g_0.exp\left(-\frac{t}{t_0}\right);\ \int_{t=0}^{\infty} h(t).dt = 1 \qquad (1)$$

where g_n and t_n are respectively the n^{th} gain and time constants given by a Fourier analysis of the transient heat equation in the wire. In the present case, only the first mode is significant. Our objective is to use a system identification method in order to monitor the variations of this impulse response, induced by changes in the operating conditions, ageing, etc. The paper is organized as follows: first, we describe the LIMBO algorithm used for fitting the model of the tested MEMS (section 2). Following the description of the readout electronics and of the experimental set-up (section 3), section 4 illustrates the performance of LIMBO. Concluding remarks are given in section 5.

2. LIMBO Algorithm

Loosely, LIMBO requires the generation of a spectrally rich signal, here a one-bit binary white noise, at the input of the unknown system. The sign s_k of the system output y_k is then measured through a 1-bit ADC (i.e. the available data is u_k and $s_k = sign(y_k)$). Using an internal parametric model of the system, its estimated output $\hat{y}_k$ and $\hat{s}_k = sign(\hat{y}_k)$ are calculated. The parametric model is then adjusted with an LMS-like algorithm, in order to minimize $(s_k - \hat{s}_k)^2$. The outputs of LIMBO are the estimations of Y_o, the offset at the input of the 1-bit ADC, and of $h(pT_s)$, $p = 0, \ldots, P-1$, the P-sample long discrete-time impulse response of the wire, where T_s is the sampling period. These outputs, collected in a single vector $\widehat{\boldsymbol{\theta}} = [Y_o, h(0), \ldots, h((P-1)T_s)]^T$, are estimated according to the following iterative procedure :

- At the k^{th} sample, the observation vector $\boldsymbol{\varphi}_k$ is defined as $\boldsymbol{\varphi}_k = [1 \quad u_k \quad \ldots \quad u_{k-P+1}]^T$. In the present case, vector $\boldsymbol{\varphi}_k$ is filled with binary samples $u_k = +1$ or -1.
- The system's analog output $\hat{y}_k$ is then estimated using $\hat{y}_k = \boldsymbol{\varphi}_k{}^T.\widehat{\boldsymbol{\theta}}_k$ where $\widehat{\boldsymbol{\theta}}_k$ are the parameters estimated at the k^{th} iteration.
- Now, if the measured sign $s_k = sign(y_k)$ of the system's analog output is the same as $\hat{s}_k = sign(\hat{y}_k)$, the estimated impulse response $\widehat{\boldsymbol{\theta}}_k$ is assumed to be correctly estimated, so that $\widehat{\boldsymbol{\theta}}_{k+1} = \widehat{\boldsymbol{\theta}}_k$. In the other case, $\widehat{\boldsymbol{\theta}}_k$ is assumed to be incorrect. It is then updated using the following correction:

$$\begin{aligned} \widehat{\boldsymbol{\xi}}_{k+1} &= \widehat{\boldsymbol{\theta}}_k - \mu \frac{2\hat{y}_k}{\boldsymbol{\varphi}_k{}^T.\boldsymbol{\varphi}_k} \boldsymbol{\varphi}_k\,, \\ \widehat{\boldsymbol{\theta}}_{k+1} &= \frac{\widehat{\boldsymbol{\xi}}_{k+1}}{\|\widehat{\boldsymbol{\xi}}_{k+1}\|} \qquad (2) \end{aligned}$$

where $\mu \in\ ]0,1[$ is a relaxation parameter scaling the convergence of the algorithm, which will be discussed in section 4.

The LIMBO algorithm features straightforward calculations, fixed-size buffer and low memory storage, which eases its implementation on a Digital Signal Processor (DSP).

3. Read-Out Electronics – Micro-Wire inside a Wheatstone Bridge

This section shows how to use a Wheatstone bridge whose differential output can be processed with LIMBO, in order to sense the changes in one of the resistances (the micro-wire) composing the bridge. For reasonable values of the current going through the bridge, over-heating of the micro-wire is low. The value of the resistance of the micro-wire $R_W(t)$ can then be expressed with a first-order expansion as:

$$R_W(t) = R_{W_0}.\left(1 + \alpha.\Theta(t)\right) \qquad (3)$$

where R_{W_0}, in Ω, is the nominal value of the resistance of the wire at ambient temperature and α the Temperature Coefficient of Resistivity (TCR) of the micro-wire, in K^{-1}. The Wheatstone bridge (Fig. 2.) is biased by a voltage

$$e(t) = e_0 + \Delta e.u(t), \qquad (4)$$

where e_0 and Δe are constant, $e_0 > \Delta e$, and $u(t) = \pm 1$ is a binary pseudo-random sequence, with sampling period T_s. Note that, since $e_0 > \Delta e$, we have $e(t) > 0$. The voltage drop $\delta V(t)$ across the differential branch can be expressed at the first order as:

$$\delta V(t) \approx \left(\alpha.\Theta(t) + \frac{\delta R_{W_0}}{R_{W_0}} - \frac{\delta R}{R}\right).e(t) \qquad (5)$$

where δR_{W_0} and δR denote resistance mismatch between the upper and lower branches of the bridge, due to fabrication process or ageing variation. Since $\Theta(t) \propto h(t) * i^2(t) \propto h(t) * e^2(t)$ and $u(t)^2 = 1$, using (4) leads to:

$$\Theta(t) \propto (\Delta e^2 + e_0{}^2) + 2.e_0.\Delta e.h(t) * u(t). \qquad (6)$$

Substitution of (6) into (5) finally gives the nonlinear expression:

$$\begin{aligned}\delta V(t) &\propto \left[\alpha.(\Delta e^2 + e_0{}^2) + \frac{\delta R_{W_0}}{R_{W_0}} - \frac{\delta R}{R} + 2.\alpha.e_0.\Delta e.h(t) * u(t)\right].e(t)\\ &\propto \left(Y_o + h(t) * u(t)\right).e(t) = y(t).e(t). \qquad (7)\end{aligned}$$

Since $e(t) > 0$, it follows that:

$$sign\left(\delta V(t)\right) = sign\left(y(t)\right) \qquad (8)$$

Thus, in spite of the nonlinear input-output relationship, LIMBO can be used to estimate both the offset Y_o and the coefficients $h(pT_s)$ of the discrete-time impulse response, from the (discrete-time) 1 bit signals u_k and s_k. However, note that if the offset is too large (i.e. the bridge is very unbalanced), s_k will be constant and there will be no way to identify the system.

From a practical point of view, the Wheatstone bridge is supplied with a 10kHz binary digital signal (e_0=1V, Δe=0.5V) through the NI6251USB 16-bit data acquisition hardware Analog Output, for convenience. The differential output signal $\delta V(t)$ of the resistor bridge is amplified using the AD625 instrumentation amplifier, with gain 300. The system's analog output is then recorded through the Analog Input of the NI6251USB. An LM311 voltage comparator provides the binary signal s_k to the Digital Input of the NI6251USB. The data acquisition hardware is remote-controlled by the Data Acquisition Toolbox® software of Matlab®, where the LIMBO algorithm is running online, either as a post-processing tool using Matlab® script programming, or in real-time using Simulink® features. Recording of the system's analog output is made in order to provide a comparison of accuracy of the system identification of LIMBO to that of other standard parameter estimation methods relying on high-resolution output signals, as shown in the next section.

4. Experimental Results – Evaluation of the performances.

This section illustrates the accuracy and the rate of convergence of the LIMBO algorithm. As mentioned in section 2, the rate of convergence of LIMBO is determined by the relaxation parameter μ. The value of μ is crucial to the

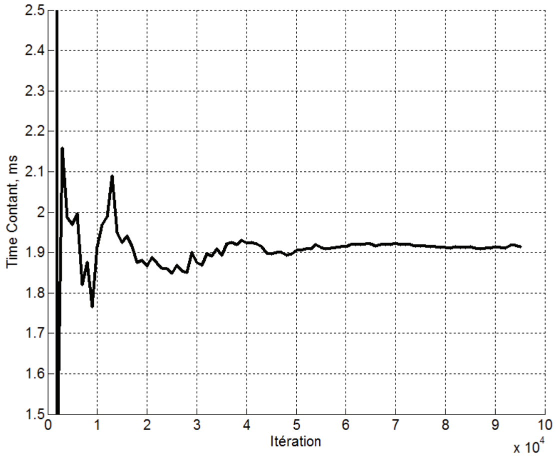

Fig. 3. Convergence status of LIMBO, in terms of time constant t_0. 20000 iterations are needed to provide a steady estimation of the impulse response of the micro-wire.

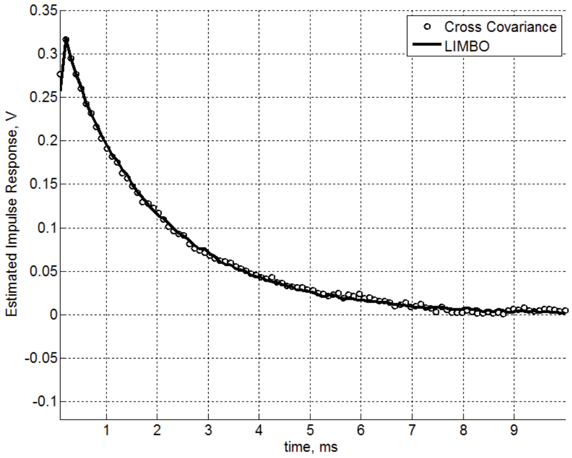

Fig. 4. Comparison of the impulse response estimated online with LIMBO with that obtained from the cross-covariance of y_k with u_k, using a 16-bit DAC and 20000 samples (batch method).

trade-off between speed and accuracy: a large value of μ results in fast convergence, but poor accuracy. On the other hand a very small value results in very good accuracy but in a very slow convergence. In the present case, we start with $\mu = 0.5$ and we multiply it by 0.97 every 1000 iterations. The impulse response is calculated using $P = 100$ parameters, which corresponds to a duration of 10ms. The time constant t_0 can then be estimated from the impulse response coefficients, using (1).

Convergence is shown in Fig. 3 in terms of time constant t_0. 20000 iterations (i.e. 2s) are needed here to provide a good estimation of the impulse response of the micro-wire. The time constant is estimated with about than 0.2% accuracy and the offset voltage with 1.0mV resolution over a ± 350mV full scale. Fig. 4 represents the impulse responses estimated after 2s with LIMBO, on one hand, and with a batch estimation of the cross-covariance of u_k and 16-bit signal y_k, on the other hand. This clearly shows that LIMBO provides results comparable to those obtained using full-scale 16-bit measurements. Note that the impulse response of the complete system is not purely exponential, as (1) would have led us to think: the rising slope at the beginning of the impulse response is in fact due to the limited bandwidth of the instrumentation amplifier, which filters out the high frequency components of the signal.

5. Conclusion and future work

We have presented in this paper a simple way of estimating several characteristics (namely offset and response time) of resistive micro-wires, with a minimal number of analog components and very low digital requirements. The proposed method and measurement setup could easily be extended to actual resistive sensors or to other sorts of impulse responses (not purely exponential). It should be stressed that LIMBO, as presented in this paper, does not allow us to identify the gain of the impulse response (since multiplying y_k by any positive constant leaves s_k unchanged). However, this can be achieved by adding a known voltage reference (either a constant or a dithering signal) at the input of the comparator. How to perform this with a minimal implementation cost is the object of ongoing work.

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